NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM

No. 1145

ROCKET POWER PLANTS BASED ON NITRIC ACID AND THEIR SPECIFIC PROPULSIVE WEIGHTS

By Helmut Zborowski

Translation

"Raketentriebwerke auf der Salpetersäurebasis und ihre spezifischen Antriebsgewichte." R-Antriebe, Schriften der Deutsche Akademie der Luftfahrtforschung
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1. INTRODUCTION[1]

Two fields are reserved for the application of rocket power plants.

The first field is determined by the fact that the rocket power plant is the only type of power plant that can produce thrust without dependence upon environment. For this field, the rocket is therefore the only possible power plant and the limit of what may be done is determined by the status of the technical development of these power plants at the given moment.

The second field is that in which the rocket power plant proves itself the most suitable as a high-power drive in free competition with other types of power plant. The following exposition will be devoted to the demarcation of this field and its division among the various types of rocket power plant.

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*"Raketentriebwerke auf der Salpetersäurebasis und ihre spezifischen Antriebsgewichte." R-Antriebe, Schriften der Deutsche Akademie der Luftfahrtforschung, Heft 1071, Nr. 82, 1943, pp. 91-126.

[1]The following report deals very largely with the results of research and development work done by a cooperative group that was set up under the leadership of Hedwig at BMW for work in this particular field.

As the basis of evaluation of the different types of power plant, the example of Schelp in using the specific propulsive weights will be followed.[2]

2. Propulsive Weights

In figure 1, the specific propulsive weights of two types of power plant[3] are shown. That is, the sum of the empty weight of the power plant and its fuel consumption, both based on the unit of free impulse[4], are plotted against the operating time for a certain speed and altitude.

The considerable flight speed of 250 meters per second at sea level was taken as the basis of the diagram.

In this diagram, in order to be able to plot the range in which rocket units operate, the specific propulsive weight of the rocket power plants, that is, the order of magnitude of the two previously mentioned components of the propulsive weight, must be determined.

The first component, the specific consumption, depends particularly upon the chosen propellant combination, that is, upon the selection of the oxygen carrier and the fuel. The choice of oxygen carrier has a substantially greater influence than any differences that would arise from the use of various fuels belonging in the high-value category.

Figure 2 shows the energy distribution of the three most favored oxygen carriers. Here pure liquid oxygen appears to be markedly superior to peroxide and to nitric acid.

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[2]For the purpose of this report, namely achievement of a rough demarcation, the "propulsive weight" is an adequate criterion of value. A more precise examination would have to include flying-range formulas, fundamental equation of the rockets, and so forth. For example, it is clear that with equal propulsive weight the power plant having the greater [NACA comment: Obviously the author means "lower."] specific consumption would in effect always be the better one.

[3]M denotes the field of the ordinary reciprocating engine and T that of the turbojet engine.

[4]The free impulse equals the impulse generated minus the resistance of the power plant.

From the total quantity of chemically released heat, however, the heat of vaporization, which in the rocket engine cannot be recovered, and the heat of dissociation, excepting that part of the heat of dissociation corresponding to the reversal of the dissociation during the expansion, must be deducted.

Nor can more than a certain proportion of the residual energy determined by the expansion ratio be converted into kinetic jet energy and then only on the assumption of ideal conversion.

From a consideration of the foregoing discussion, the theoretical consumptions are such that the superiority of oxygen appears greatly reduced.

The theoretical specific consumptions and the corresponding consumption volumes are shown in figure 3. The specific consumption of oxygen is only a few percent better than that of peroxide and nitric acid, whereas nitric acid shows by far the smallest specific volumetric consumption.

If equal excellence of design and construction and equal structural weights are assumed, this smaller specific volume results in a noticeable increase in maximum propellant loading. This increase has a strong influence on maximum possible performance in the aeronautical and especially in the ballistic application of rocket power plants.

The specific volumes, however, also have a substantial influence on the specific values themselves, namely on the consumption per unit thrust. The coupling of the specific consumption with the specific volume through the resistance of the surrounding medium may be expressed for a few limiting cases by means of simple relations.

Thus, for the simplest case, that of the wingless body in a state of uniform motion with propellants of equal heat value, the ratio of the specific consumptions multiplied by the ratio of the specific weights with an exponent of 2/3 is constant. [NACA comment: The assumption has been made that "hoch 2/3" means "with an exponent 2/3" although substitution of the actual coordinates of the steepest curve in figure 4 in the formula $y.x^{2/3} = K$ is not correct as K successively equals 0.924, 0.952, 0.89, and 1+.]

This relation is shown in figure 4. From this figure may also be seen that the influence of the specific volumes becomes smaller when wings are added to the body, that is, with increasing ratio of this added resistance to the total resistance and with increasing values of c_a. During the actual process of acceleration, the direct influence of the specific volume is relegated even more markedly to the background.

The above statements will be briefly illustrated by means of a practical example.

In figure 5, the flight ranges of rocket projectiles are plotted against the ratio of propellant weight to take-off weight for three different loadings per unit area[5]. The values are based on nitric acid; the loadings in the case of oxygen are in accordance with different densities.

For this representation, it should further be noted that a ballistic loading per unit area of 0.7 kilogram per square centimeter is unlikely to be attained; it is much more likely that the attainable loading will be about 0.3 kilogram per square centimeter. Consequently, the two upper solid curves and the corresponding dashed curves are eliminated for comparative purposes.

Furthermore, when it is taken into account that, with equal excellence of design and construction, the ranges attainable with nitric acid correspond to those attainable with oxygen at somewhat larger values of the ratio of propellant weight to take-off weight, it is seen that the greater attainable ranges always correspond to operation with nitric acid.

As a consequence of the low specific volume and of the specific consumptions that are actually attainable, if the dissociation and the practicable expansion ratios are considered, highly concentrated nitric acid is superior to other oxygen carriers.

The additional great advantages of nitric acid, that is, lower vapor pressure, advantageous freezing point of -42° C, desirable ignition behavior, ease of obtaining complete combustion, and stable structure, which eliminates spontaneous decomposition, as well as the facts that nitric acid is easily obtainable, may be transported readily, and stored indefinitely and a number of metallic, ceramic, and synthetic materials available that are either adequate or absolute proof against nitric acid, clearly make it the best oxygen carrier for rocket power plants.

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[5]Namely, the loadings per unit area of the projectiles without propellant.

Lutz and Hertel called attention in their reports to the great advantages of spontaneously reacting propellant combinations in facilitating the lightest and simplest construction of rocket power plants.

Because the successful development of fuel combinations that can be produced in adequate quantity satisfy all the requirements for rocket fuels and are capable of ready reaction with nitric acid, for example, the ignition delays from contact until the appearance of the flame reaction in the BMW fuels amount to less than one thousandth of a second, creation of rocket power plants of the simplest mechanical construction[6] using nitric acid recently has also been possible. Additional stiffer requirements for the resistance of nitric acid to extreme cold (resistance to arctic conditions) have been met. That is, lowering of the freezing point of nitric acid by means of admixtures[7] was possible. For example, the addition of 4 percent by weight of iron trichloride ($FeCl_3 \cdot 6H_2O$) effected a lowering of the freezing point from -42° C without admixture to -56° C. Mention should be made that with most of the spontaneously reacting fuels this admixture also resulted in a substantial reduction of the ignition delay.

Nitric acid can be improved with regard to greatest density of propellant and lowest specific consumption. If oxides of nitrogen[8] are dissolved in nitric acid, specifically about 40 percent by weight of nitrogen dioxide (NO_2 or N_2O_4), the density of the nitric acid can be raised from 1.52 to 1.62 and thereby the volumetric consumptions can be decreased by about 6.5 percent and the gravimetric consumptions can be lowered by about 2.5 percent thus substantially improving the consumption per unit thrust. With this goes a lowering of the freezing point and an increase in ignitability, as well as a substantial improvement in the corrosion qualities. The basis of this improvement is the freedom of the acid from water, which results from the newly established equilibrium condition. Thus in this case, an improvement in the corrosive behavior combined with a reduction in the consumption exists, whereas in the case of mixed acids[9] the improvement of the corrosive qualities involves an increase in the consumption.

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[6]Spontaneously reacting propellants eliminate the otherwise necessary special devices for ignition, as well as the obstruction of the propellant inlet into the combustion chamber by the ignition arrangements.

[7]Water among other things.

[8]The most suitable are nitrogen dioxide and nitrogen pentoxide.

[9]That is, a mixture of nitric and sulfuric acids.

The fine points of the possibilities of improvement, especially with respect to consumption, through selection and development of suitable fuels will not be discussed here; in this connection reference is made to the report by Hertel.

Only the question of the suitable proportions of nitric acid and fuel remains to be considered. As shown in figure 6, the minimum consumption is not secured at the stoichiometric ratio as calculated for complete combustion but these minimums lie in the region of excess fuel.

In the figure are shown consumptions, temperatures, and specific weights of the combination for alcohol (methanol, CH_3OH) and for a representative of the spontaneously reacting fuels (orthotoluidine, $C_6H_4NH_2CH_3$).

Fortunately in this case both these statistical data on the process of combustion and certain specific qualities of nitric acid to be cited subsequently agree in requirement of excess fuel.

By operation with an excess of fuel, not only are the optimum specific consumptions obtained but also, as will be shown subsequently, exhaust gases free of oxides of nitrogen in practical operation.

The selection of nitric acid as the best oxygen carrier determines the order of magnitude of the consumptions per unit thrust. Attention will now be turned to the other component of the propulsive weight, namely the specific power-plant weight.

The specific power-plant weight is primarily dependent on two factors: first, the method of injecting the propellant and second, the magnitude of the combustion-chamber pressure selected.

The customary fuel-supply systems are presented in figure 7 for comparison.

The construction shown at the top is that of the classic form of the rocket, the solid-fuel power plant, probably the oldest combustion power device of mankind. The other sketches show the systems of supplying fluid propellants.

In the second power plant shown, the supply is accomplished by compressed gas displacing the propellants. This unit will be referred to briefly hereinafter as the "compressed-gas apparatus."

In the sketch at the bottom, the fuel supply is effected by pumps driven by a turbine that is supplied with the same propellant as used by the rocket. This unit will hereinafter be referred to as the "pump apparatus."

The remaining diagram is that of a unit having differential pistons. The supplying of the propellant is accomplished by the combustion gases through the medium of a free piston. The excess injection pressure is obtained from a difference between the piston surface area exposed to the gas and that exposed to the liquid. This unit will hereinafter be referred to briefly as the "piston apparatus."

Before the different types of power plant can be compared with each other, the optimum operating pressures must be estimated for each type.

For this purpose, investigation of the influence of the combustion-chamber pressure on the consumption and on the weight of the installation is necessary.

An increase in combustion-chamber pressure has an advantageous effect on consumption in two ways: first, through the reduction in the degree of dissociation with increasing combustion pressure, as shown in figure 8, where a dimensionless characteristic value for consumption is plotted against combustion-chamber pressure and second, through the better pressure ratio for the expansion of the jet that a higher combustion-chamber pressure involves.

In figure 9, this second effect is also represented by means of a dimensionless consumption characteristic plotted against the combustion-chamber pressure. In consideration of the fact that the magnitude of the back pressure also has a considerable influence on the expansion ratio, the characteristic values were plotted for three different back pressures corresponding to three different altitudes.

The diagram is made still more comprehensive by the addition of the dashed curves, which express the limitations imposed by the practical limit on the possible expansion ratios. The expansion ratio is taken as 50 in this case.

It should be noted that, as preliminary investigations have shown, the limitation of the expansion ratio is not determined by technical cooling factors but results from aerodynamic and gas-dynamic considerations involved in the most efficient design of the tail of the aircraft.

In accordance with what has previously been said, the consumption characteristic simply reaches no minimum in the case of the solid-fuel rocket because the curve of consumption shows only a decreasing tendency as the combustion-chamber pressure rises.

For the piston and compressed-gas apparatus, however, as a consequence of the cost of forced supply, minimums, which occur, to be sure, at very high combustion-chamber pressures, are found.

In the turbine unit, these minimums, especially when the efficiencies of turbine and pumps are introduced into the calculations, lie at substantially lower pressures. These relations are shown in figure 10.

Thus with respect to consumption, an optimum combustion-chamber pressure of 75 to 100 atmospheres absolute apparently exists for operation at sea level; however, the pressure is already reduced to about 25 atmospheres absolute at an altitude of 16 kilometers.

If the values for consumption are now combined with the constructional weights, which are also a function of the combustion-chamber pressure, the specific propulsive weights for the different types of power plant and for various operating periods are obtained as functions of combustion-chamber pressure.

In figure 11, the theoretical specific propulsive weights are plotted against the combustion-chamber pressure at an altitude of zero for operating times of 10 and 100 seconds.

The actually optimum combustion-chamber pressure is for all units substantially lower than that based on the concept of consumption alone. Thus, at sea level for piston and compressed-gas units the pressure amounts to about 25 atmospheres absolute and for the pump unit to about 50 atmospheres absolute; for the pump unit at an altitude of 16 kilometers the pressure is about 18 atmospheres absolute.

The minimums of the time-dependent curves were then plotted against time in figure 12 in which limiting values of specific constructional weights and of specific propulsive weights are plotted against the length of the full thrust period. The dashed curve represents approximately the status attained at the present time.

In figure 13, this curve, which is based on weighted constructional weights, is again shown. This diagram has been extended by showing the section of the curve applying to solid-fuel rockets.

From this figure, the region in which each type of rocket power plant has the most advantageous propulsive weight can be found.

The following brief remarks are offered as to the character of the curves:

The limiting value toward which the curve for the pump power plant asymptotically tends is the value of the specific consumption including that of the turbine increased by the associated tank weights. This value is therefore only a few percent greater than the combustion-chamber consumption alone.

The curve for piston and compressed-gas units follows a similar course but the limiting value is considerably higher because the pressure-resistant construction results in a greater associated tank weight.

In the solid-fuel rocket, the explanation for the minimum and for the branch of the curve that rises again with time is to be found in the decrease of stability at higher temperatures. The rising branch of the curve flattens out in its subsequent course and again tends toward a limiting value determined by the stability to heat at the highest temperature reached.

The curves provide bases from which to estimate what can be accomplished with rocket power plants and make possible the advantageous layout of even first tentative designs.

In figure 14, the scope of figure 1 is extended by including the envelope curve from figure 13. In terms of the general order of magnitude, this figure gives the range of application appropriate to the rocket power plant as compared with the other propulsive systems.

Some basic considerations remain to be mentioned in connection with the two diagrams that embody the results of the previous presentation:

For more exact evaluations, these representations must be extended to include the variations with speed and altitude.

For an adequate evaluation of any power plant both the consumption and the constructional weight are to be based on the free thrust, that is, useful thrust.

Fundamentally, figure 14, which is based on an altitude of 0 kilometers, shows that a region exists in which rocket power plants are superior to other propulsive systems. The scope thus originally assigned to rocket propulsion is considerably enlarged as altitude increases.

As to the boundaries between the fields of the various types of rocket and between rocket propulsion and other propulsive systems, it should be noted that the specific propulsive weight does not only represent an index of what is practically possible, but may also be used as an index for most economical design.

Thus, in all applications in which the specific propulsive weight is not the only determinant of the attainability of a prescribed goal, the mechanically simpler unit should still be used even in that part of the range in which by using a more mechanically complicated unit a reduction in the specific propulsive weight could be achieved. This consideration is particularly applicable when, as in the case of projectile propulsion, the unit can be used only once because the economic cost per kilogram of constructional weight may be as much as 100 times the cost per kilogram of propellant.

Because, according to the preceding diagrams, the mechanically simpler types always correspond to the shorter operating periods, the preceding reasoning leads in effect to an extension of each of the indicated ranges in the direction of longer operating periods.

The great advantages to be secured by using various combinations of different propulsive systems[10] and of different types of rocket propulsion[11] can also be deduced from figures 13 and 14.

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[10]That is, the combinations MT, MR, TR, and MTR. [NACA comment: See footnote 3, page 2.]

[11]That is, for example, the combination of pump with compressed-gas, pump with solid-fuel, and compressed-gas with solid-fuel mechanisms.

3. OPERATING CONSIDERATIONS

Before this report is concluded with a mention of the existing lacunae in development and more especially in basic research, which must be filled, further discussion of certain specific characteristics of nitric acid will be desirable.

Highly concentrated nitric acid, which is precisely the only kind that is appropriate as an oxygen carrier for rocket power plants because of the advantageous consumption figures obtainable with it, causes metals that otherwise are readily oxidizable, for example iron, to become passive; therefore, these metals are not attacked by nitric acid, which is free from water. This passivity is exhibited in larger degree by aluminum and also by chromium.

This characteristic and the fact that the acid is hygroscopic point to the necessity of sealed storage in order that the container materials will not be excessively attacked by diluted acid and traces of nitrous acid that are formed as a result of atmospheric moisture.

Steels having V 2 A characteristics, that is, highly alloyed nickel and chrome steels, may be cited as metallic materials that are particularly resistant even to diluted acid.

Ceramic materials, such as porcelain, glazed stoneware, and baked enamels, are not attacked at all by nitric acid and most varieties of glass are completely resistant to it.

As coating and calking materials, there are available synthetics developed by the I. G. Farben Industry Inc., namely highly polymerized hydrocarbons based on ethylene, such as the Oppanols, particularly Oppanol B 200 (molecular weight 200,000), and the Lupolenes, especially Lupolene H (molecular weight 25,000 to 30,000). Among fibrous materials, asbestos and PeCe fibers (polyvinyl chloride) show complete resistance to the acid.

As sealing liquids possessing adequate passivity toward nitric acid, paraffin oil, pure, DAB 6, and oils and emulsion polymers developed by I. G. Farben Industry Inc., such as SS-oil 906, are available. By use of the materials mentioned, performance of all necessary handling of nitric acid and maintainance of reliable operation is possible.

As examples of the safe, even clean, filling of power plants with nitric acid, figure 15 shows the open filling of a small unit, figure 16 shows the filling of the BMW-511 unit, and figure 17 shows the filling of an 8-cubic-meter test-stand installation[12].

There has been much discussion of the alleged especial poisonousness of the exhaust gases when operating with nitric acid. The nitrous gases, particularly nitrogen dioxide, are powerful lung poisons.

Nitric acid decomposes reversibly at relatively low temperatures with the formation of nitrogen dioxide whereas from about 1700° C [NACA comment: An obvious error in the temperature has been corrected.] it undergoes an irreversible decomposition without the formation of any nitrogen oxides.

The numerous oxides that can be formed with nitrogen, which is 2-, 3-, 4-, and 5-valent, with one exception, nitric oxide (NO), have in common a more or less marked instability. Some nitrogen oxides decompose even at rather low temperatures, others at higher temperatures but all these temperatures are far below that which is obtained in the combustion chamber.

Nitric oxide, however, which at lower temperatures combines with oxygen from the air to form nitrogen dioxide, is formed in ever increasing quantity at temperatures above 700° C. [NACA comment: An obvious error in the temperature has been corrected.]

The decomposition equations for the reactions mentioned are:

$$4\ HNO_3 \rightleftharpoons 4\ NO_2 + 2\ H_2O + O_2 \quad - 61.6 \text{ g-cal}$$

$$4\ HNO_3 \rightleftharpoons 2\ N_2 + 2\ H_2O + 5\ O_2 \quad - 29.2 \text{ g-cal}$$

$$2\ NO_2 \rightleftharpoons 2\ NO + O_2 \quad - 27 \text{ g-cal}$$

$$2\ NO \rightleftharpoons N_2 + O_2 \quad + 43.2 \text{ g-cal}$$

On the basis of these relations, the formation of nitric oxide and of the nitrogen dioxide that nitric oxide forms in air can easily be prevented by proper operating arrangements. At combustion-chamber

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[12] In the development of ground equipment for the troops, the fundamental requirement of sealed filling arrangements must be met. A vapor-return line and self-closing couplings should therefore be provided.

temperatures above 1600° C, practically complete decomposition of the nitric oxides is assured. If in addition it is insured by an appropriate excess of fuel that a deficiency of oxygen makes impossible the thermal formation of nitric oxide in the hottest parts of the combustion chamber, that is, where the already completed combustion yields temperatures of over 2700° C, even the combustion-gas jet obtained in routine operation will be free of nitric oxide.

Practice confirms the correctness of this reasoning. Figure 18 shows ignition in the BMW-510 unit, which is accomplished by the use of spontaneously reacting fuels.

The beginning of combustion in the same power plant may be seen in figure 19.

The two following figures, 20 and 21, show this power plant operating at full thrust. Combustion free of nitric oxide is clearly evident in both photographs.

The beginning of combustion in the BMW-511 unit is shown in figure 22[13], whereas in figures 23[13] and 24 the same unit is shown in normal operation.

From these photographs, it is also evident that the combustion is free of nitric oxide. These photographs of jet operation show the combustion of nitric acid and methanol. Nitric oxide-free combustion, however, is equally attainable with other fuels. In this connection attention is called to figure 18; furthermore, figure 25 shows the combustion chamber of the BMW-548 unit operating with spontaneously reacting fuels.

4. FURTHER DEVELOPMENT

The development of rocket units has made considerable strides in the recent past; for example, specific consumptions at sea level of 4.9 kilograms per ton second have been attained in reliable and reproducible operation. The desire for refinements and the necessity for the achievement of minimum structural weights and consumptions result in a vast number of individual efforts, which are collectively decisive.

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[13]The stress-carrying sheet-metal cover of this unit, to which the combustion chamber would ordinarily be attached, has been removed in order to show the operation of the differential piston and the strength of the piping.

The success or failure of these efforts depends a great deal upon how far they will be founded upon and carried out as basic research. Certain of these problems that must be solved will be subsequently mentioned but one of them will be discussed at this point.

Many current needs call for a power plant with the most advantageous weight per unit thrust of the rocket power plant but at the same time the power plant must show so much better consumption that it cannot be designed in view of the limiting values. The induction of an air charge would be a means, especially in regions of greater air density, of reducing the specific consumptions far below those of orthodox rocket units. Because continuous admixture of air can produce no decisive results, the tidal air induction would have to be intermittent. An intermittently operating rocket unit of simple construction, however, would require spontaneously reacting propellants having very short ignition times. Because these propellants are now available, the development of such units seemingly could be undertaken with a prospect of success. The mechanical complexity of such a unit, if designed to operate as a gas-pressure compressor, would be substantially less than that of a unit using pumps.

As a first rough approximation, consumptions up to about 30 percent lower than those of the orthodox rocket unit might be expected at sea level. Of course, these consumptions will rise with increasing altitude finally equaling, or in certain circumstances even slightly exceeding, those of orthodox rocket units.

Because an important class of rocket units, namely rocket projectiles, is not receiving specialized discussion today[14], this section of the present report will be concluded by presenting a diagram (fig. 26), which shows the range as a function of the ratio of useful load to propulsive weight for the simplest case, namely the noncatapulted, wingless, one-stage rocket projectile.

As power-plant weights on which to base this diagram, the nominal limiting values plus 50 percent were taken. The weights are therefore too favorable and cannot be attained in practice, particularly in first attempts. The practical ranges will therefore be somewhat less than those shown here. On the other hand, the difference between pump, compressed-gas, and piston units will be somewhat less.

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[14]Working session of the German Academy of Aeronautical Research, August 5, 1943.

For these curves, a propellant load of 10 tons was assumed. For larger projectiles, the ranges would be somewhat increased over those given; in the case of smaller projectiles, for example with a 1-ton propellant load, the ranges would be reduced 10 percent on the average.

5. RESEARCH PROBLEMS

Some research problems will now be listed, the solution of which would substantially promote the development of rocket power plants:

1. Production of a chromium plating free of holes and cracks and adhering firmly to steel or of chromicized surface layers.

2. Development of nitric-acid-proof constructional materials of high heat conductivity and great resistance to heat.

3. Survey of the possibilities of increasing to an adequate degree the resistance to cyclical temperature changes of fire-resistant constructional materials at temperatures above 2500° C.

4. Investigation of the flow relations in combustion chambers and thrust nozzles including the actual turbulence.

5. Investigation of the flow relations in the gas-pressure compressor.

6. Clarification of still unanswered questions in connection with tidal air induction.

7. Clarification of the reaction kinetics of nitric-acid fuel systems.

8. Survey of possibilities of increasing the reaction speeds of such systems.

9. Determination of the time required to establish the dissociation equilibrium with rising and with falling temperatures.

10. Survey of the possibilities of synthetic production of spontaneously reacting fuels of highest heat value.

11. Determination of the temperature and the combustion area in the combustion chamber, derivation of a combustion chamber of minimum volume, and investigation of the relation between combustion-chamber volume and specific consumption.

12. Investigation of friction conditions in the thrust nozzle (limitation of the optimum nozzle by friction).

13. Investigation of the influence of the area of the nozzle mouth upon the total resistance (aerodynamically and gas dynamically) and on the consumption per unit thrust.

14. Investigation of heat transfer at extreme velocities and temperatures (as in thrust nozzle).

15. Determination of the heat conductivity and the viscosity of the combustion gases at their temperatures.

16. Determination of the heat conductivity of nitric acid at various temperatures.

17. Determination of the heat conductivity at high temperatures of the materials used in the construction of combustion chambers.

18. Determination of the heat transfer at extreme velocities to the nitric acid on the cooling-medium side.

19. Determination of the basic constructional forms of injection nozzles that will insure the most rapid initiation of combustion and the most thorough combustion.

6. SUMMARY

By going beyond the purely thermodynamically and gas dynamically determined relations to include aerodynamics and by application of the criterions of practice, which must be concerned above all with large-scale military use and the problem of transport and supply, technical highly concentrated nitric acid has been shown to be the best oxygen carrier for rocket power plants.

In terms of order of magnitude, the scope of application of nitric-acid rocket power plants was determined as well as the component ranges of the chief examples of typical propellant-supply systems. This scope of use lies between that of solid-fuel rocket power plants and that of

turbojet units but for expendable items and for higher altitudes the limits given are shifted in the direction of longer operating times.

Specific characteristic values that will enable both the aerodynamic and the ballistic experts to determine the best over-all design for their projects have been defined.

It has been shown that nitric acid may be handled simply and with a high degree of safety and that elimination of the formation of nitrous gases during the combustion of nitric acid is easy.

The successful development of spontaneously reacting fuel combinations with short ignition periods now makes possible the development of pump-supplied nitric-acid power plants of mechanically simple construction.

The determined effort to reduce still further the ignition periods of such fuel combinations has succeeded to such a degree that the development of a mechanically very simple intermittent rocket power plant making use of tidal air induction may today be undertaken with prospects of success. With such a unit, a decisive reduction of weight per unit thrust in the region of greater air density may be expected and this reduction will result in a substantial increase in the remaining flying time available for higher altitudes.

Some open questions for research and development work have been mentioned in which connection it should be remembered that pure research in particular can make very important and decisive contributions to further successful development.

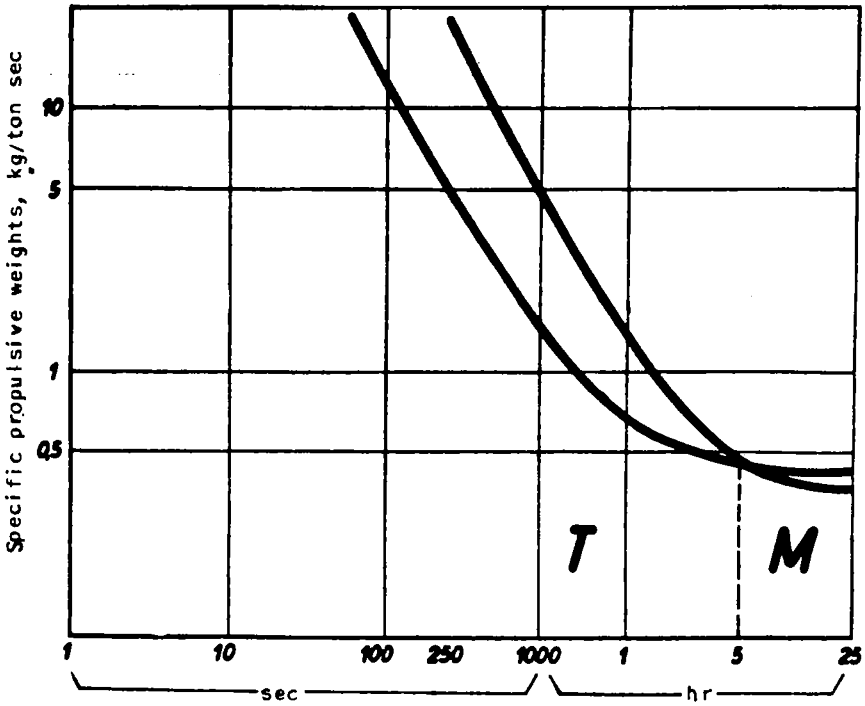


Figure 1. - Specific propulsive weights.

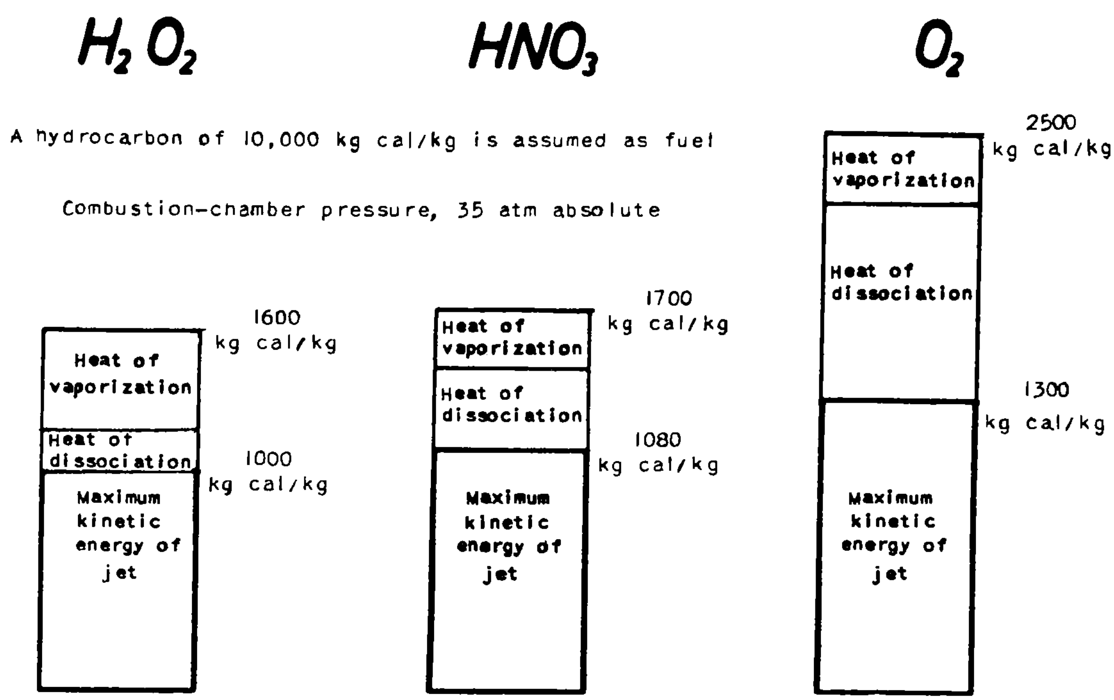


Figure 2. - Energy distribution.

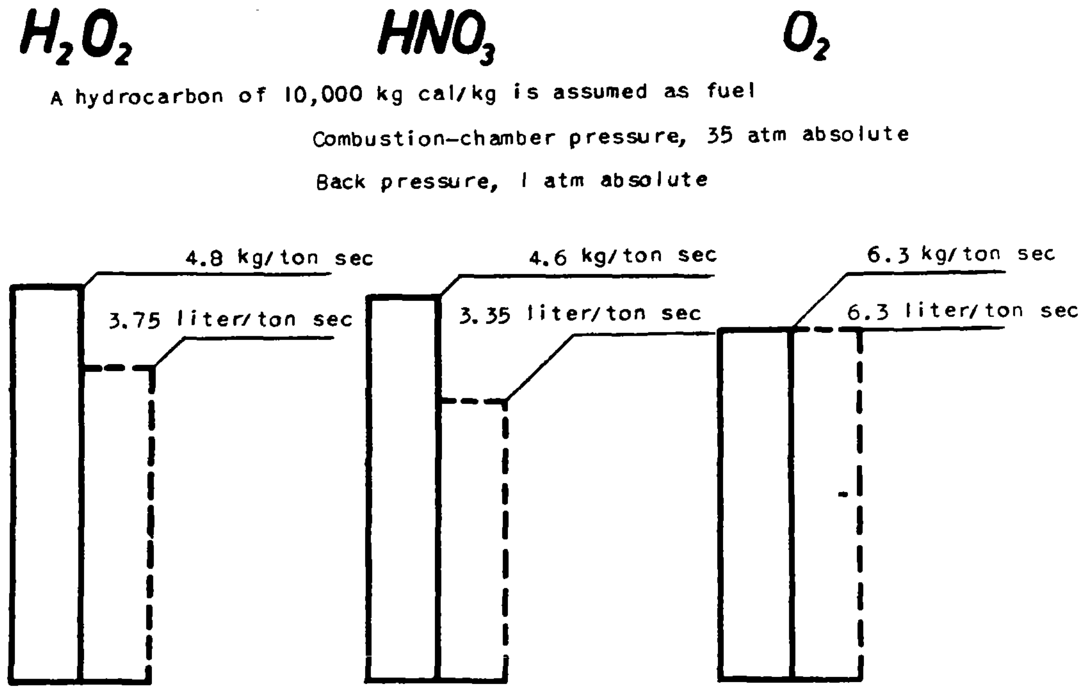


Figure 3. - Theoretical specific consumption in kilograms per ton second and liters per ton second.

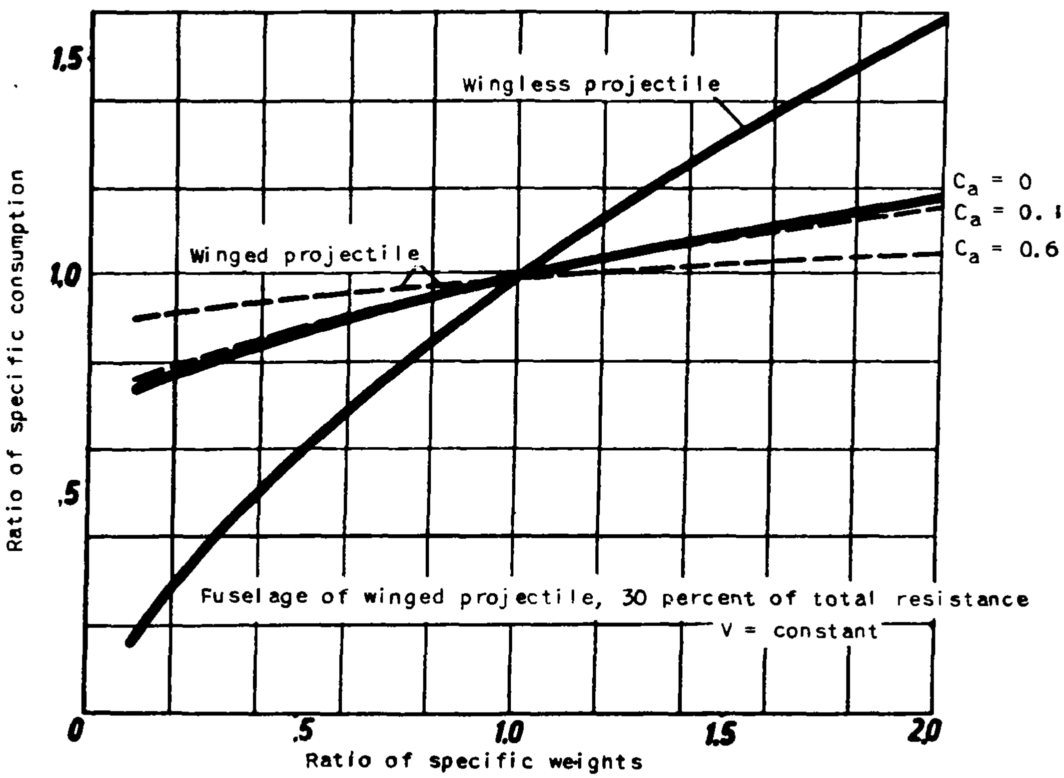


Figure 4. - Relation between specific weight and specific consumption for rocket projectiles.

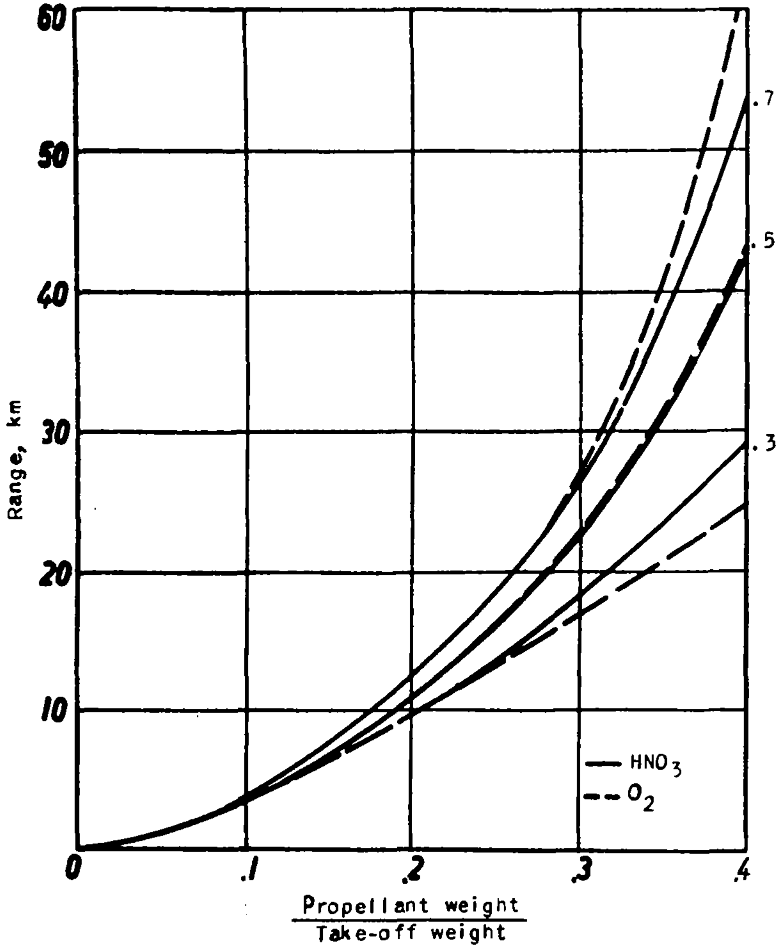


Figure 5. - Flight range of rocket projectiles based on HNO_3 and on O_2 at various loadings per unit area.

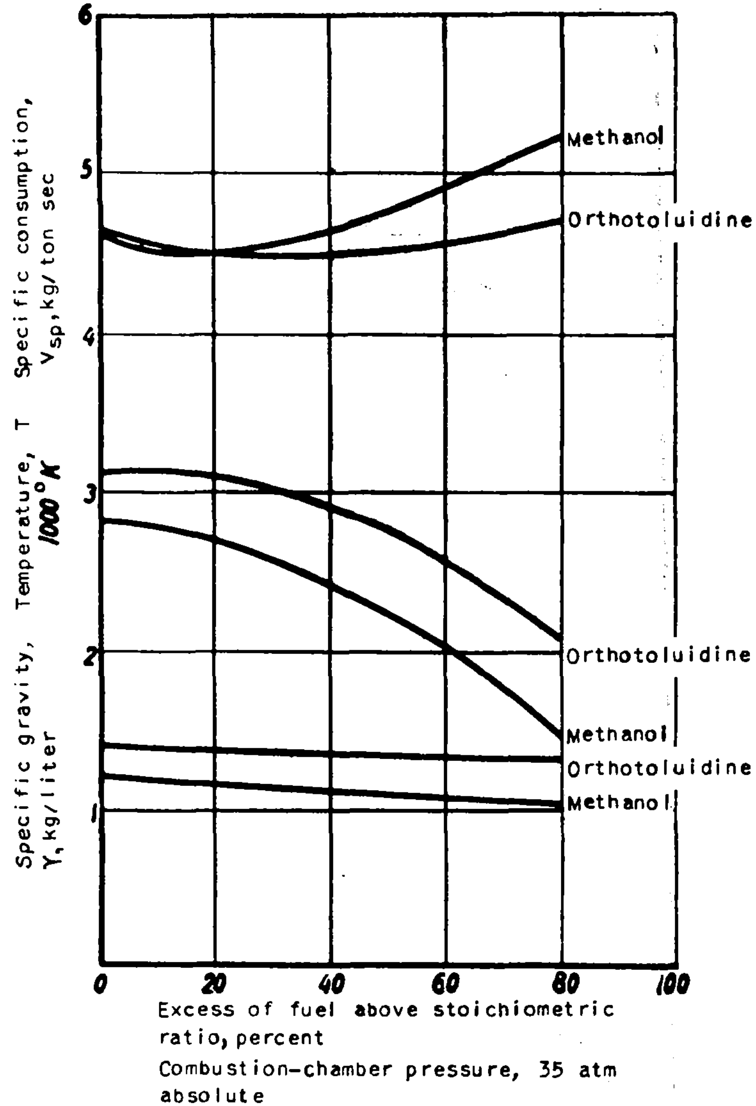


Figure 6. - Influence of excess fuel in combustion with nitric acid.

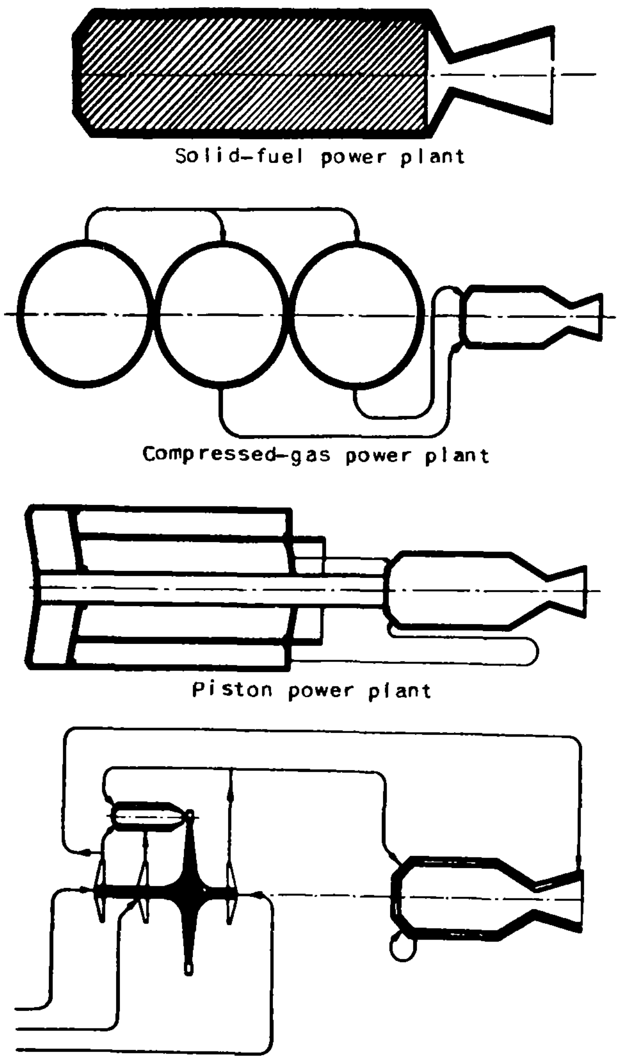


Figure 7. - Basic forms of rocket power-plant construction.

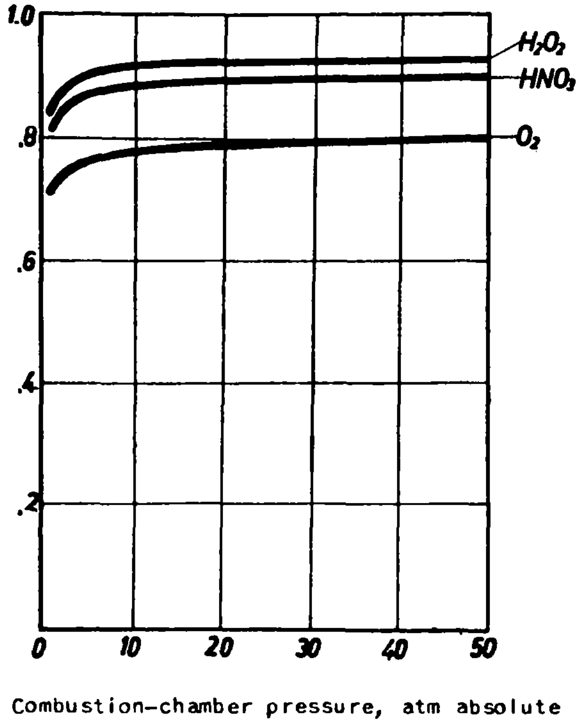


Figure 8. - Influence of combustion-chamber pressure on specific consumption as chamber operates through dissociation process.

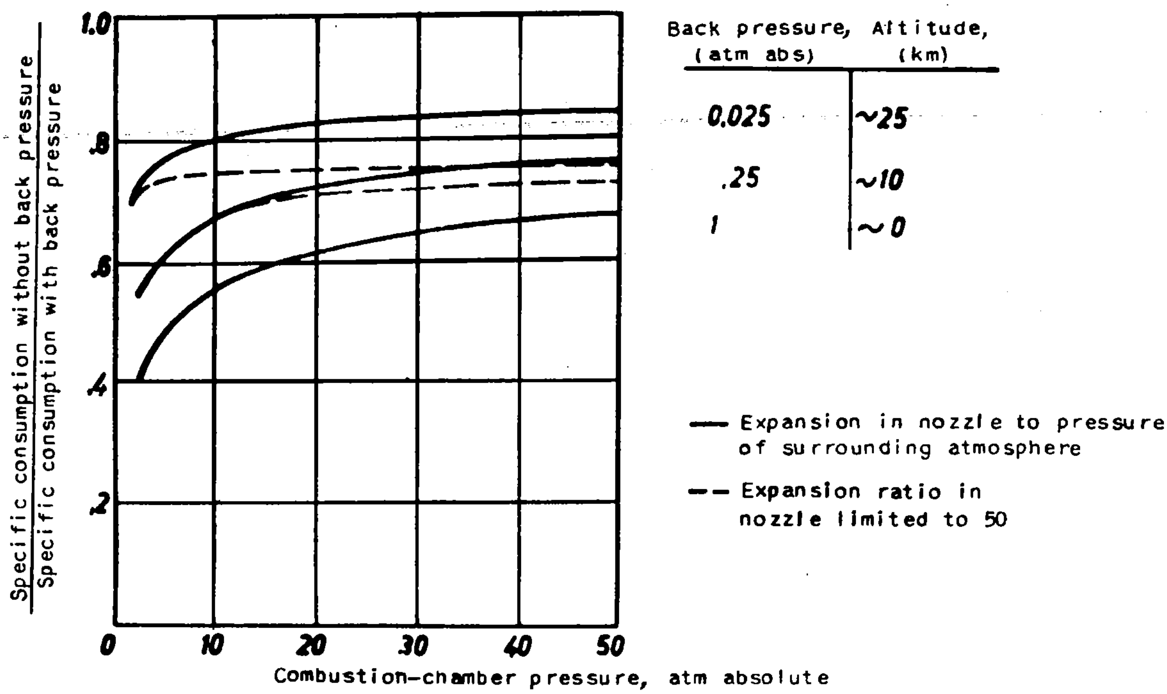


Figure 9. - Influence of combustion-chamber pressure on specific consumption as chamber operates through variation in expansion ratio.

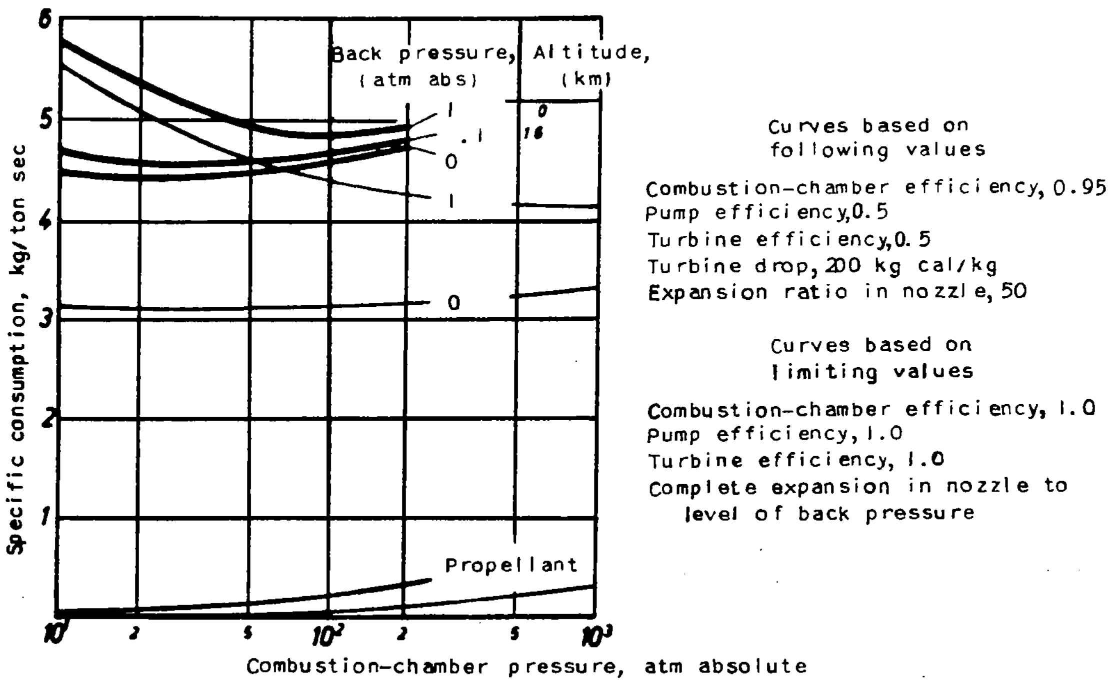
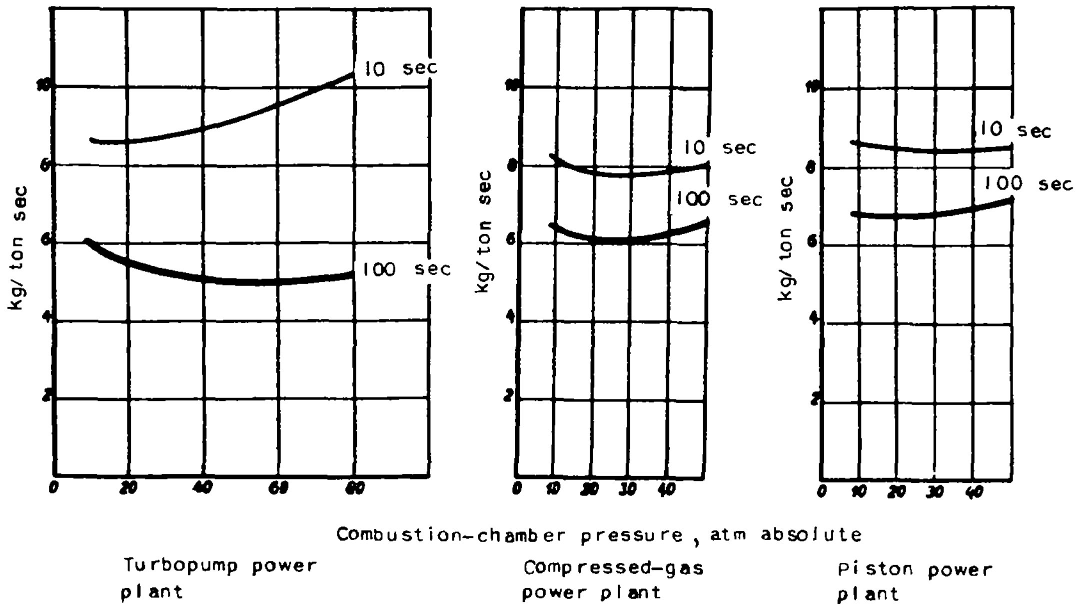


Figure 10. - Optimum combustion-chamber pressure for rocket power plants with turbopump fuel supply.



Back pressure	1 atm absolute
Specific weight of propellant	1.4 kg/liter
Specific consumption at combustion-chamber pressure of 35 atm absolute	5 kg/ton second

Figure 11. - Limiting values of specific propulsive weight in kilograms per ton second as function of combustion-chamber pressure for 10 and 100 seconds of full thrust.

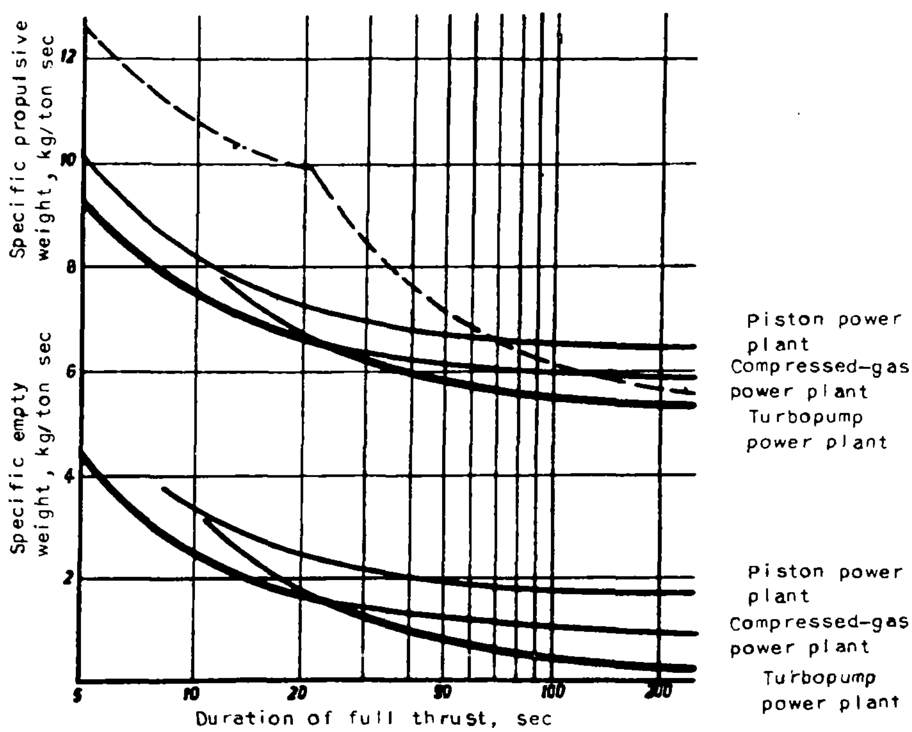


Figure 12. - Limiting values of specific empty and propulsive weights of rocket power plants with liquid fuels.

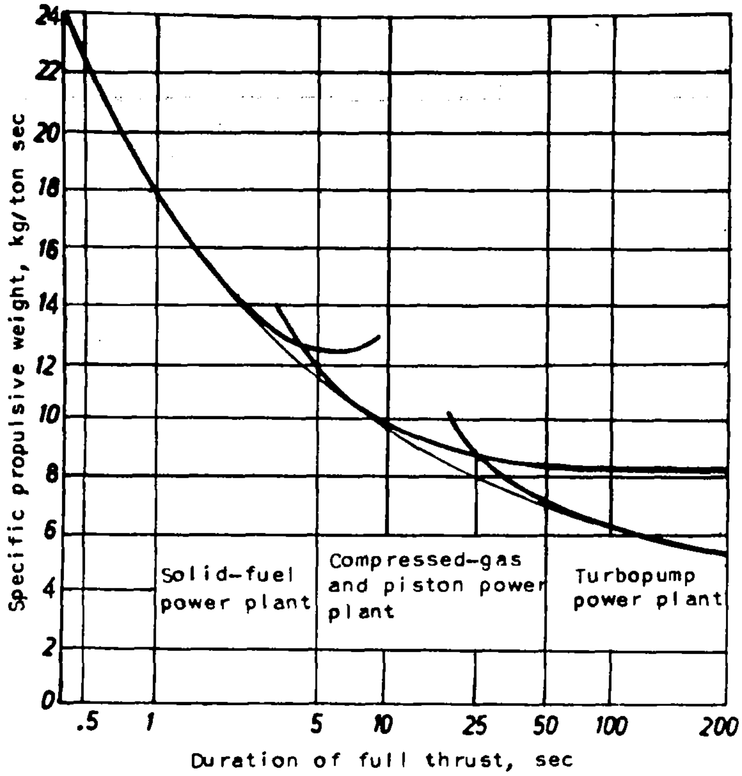


Figure 13. - Specific propulsive weights derived from weighted power-plant weights.

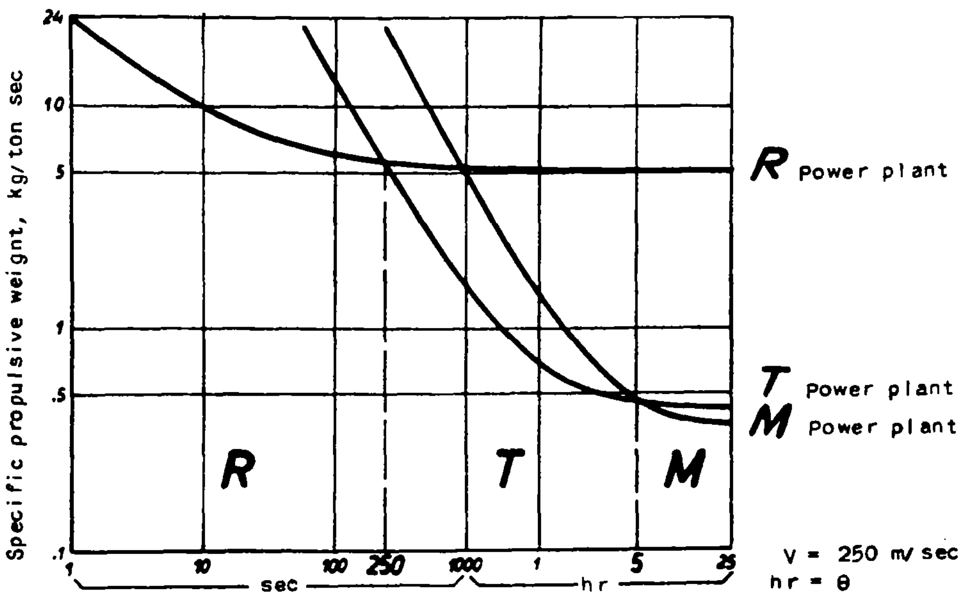


Figure 14. - Specific propulsive weights.
[NACA comment: R, rocket; T, turbojet; M, reciprocating.]

Figure 15. - Filling BMW-548.

Figure 16. - Filling BMW-511.

Figure 17. - Filling pump for BMW-510.

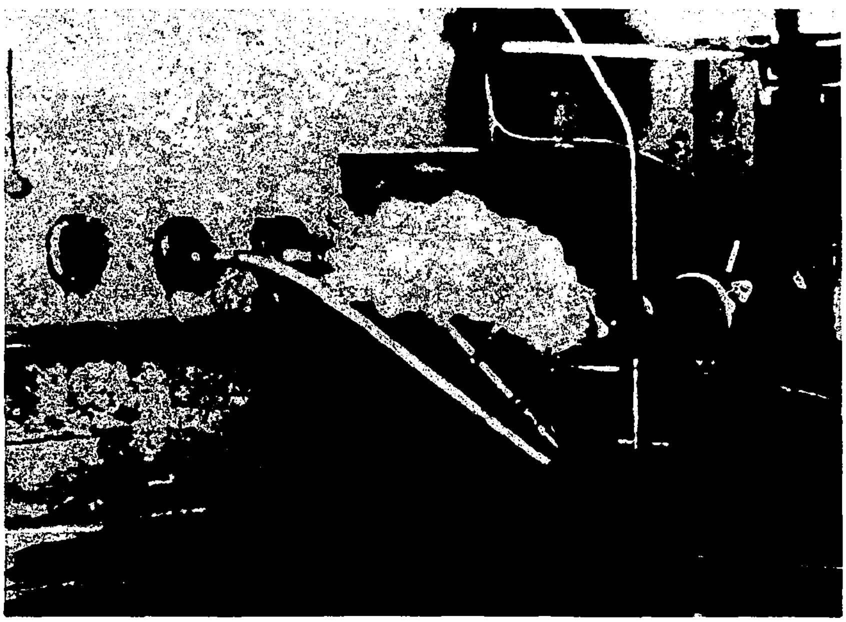


Figure 18. - Start of ignition in BMW-510.

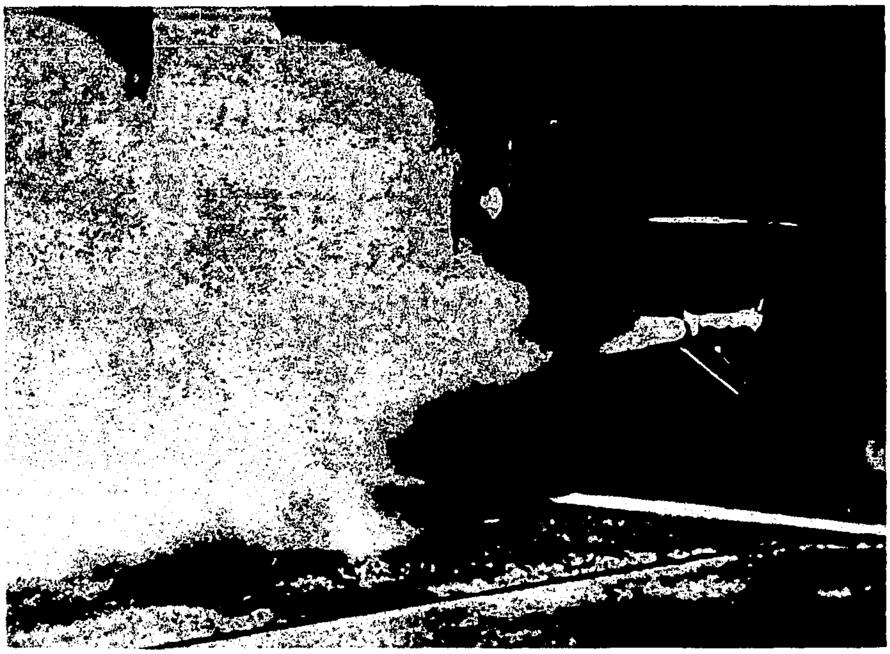


Figure 19. - BMW-510 in operation (start of combustion).

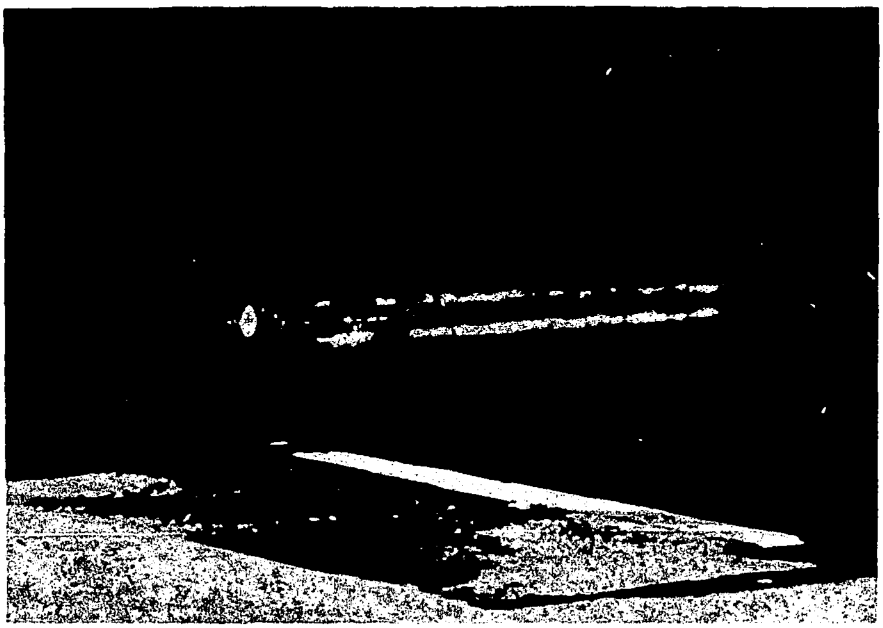


Figure 20. - BMW-510 in operation.

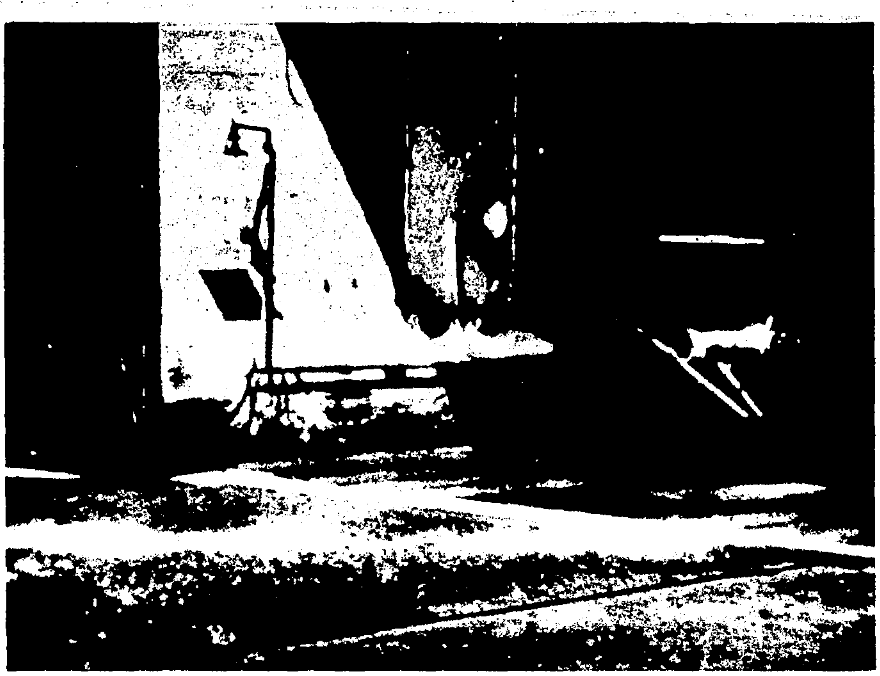


Figure 21. - BMW-510 in operation.

Figure 22. - BMW-511 in operation (start of combustion).

Figure 23. - BMW-511 in operation.

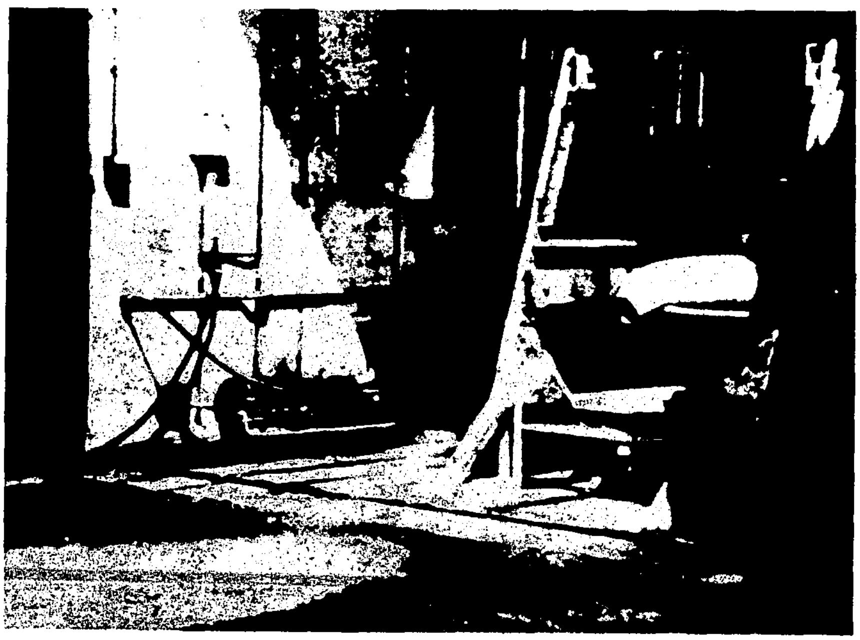


Figure 24. - BMW-511 in operation.

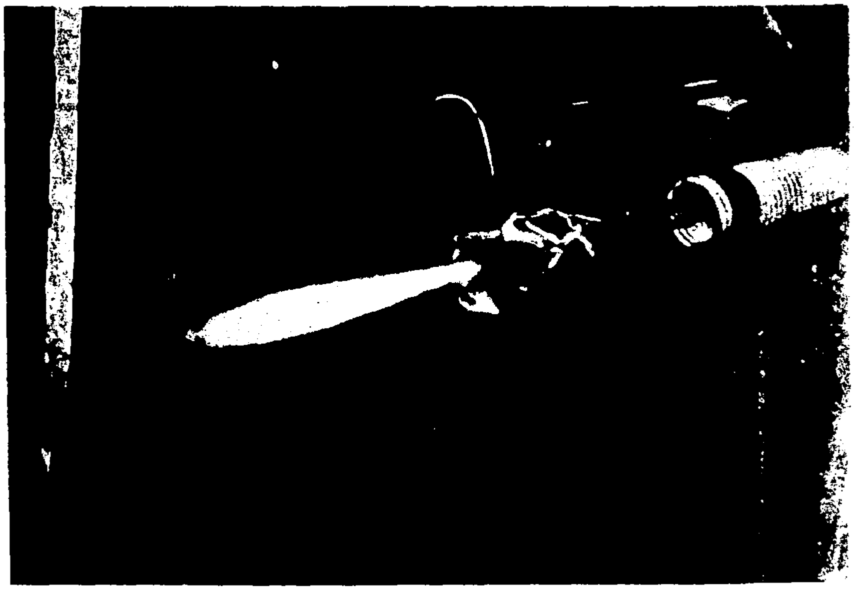


Figure 25. - Operation of combustion chamber of BMW-548.

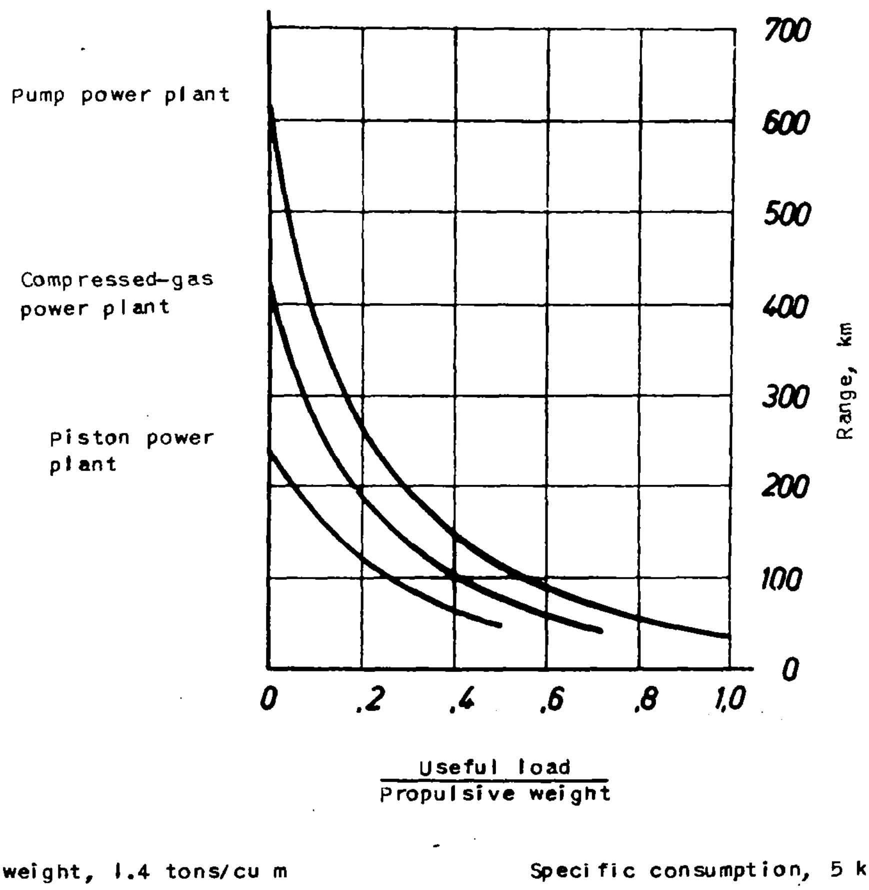


Figure 26. - Flying range of large-caliber rocket projectiles without catapulting.

DISCUSSION

Busemann: I thank Mr. Zborowski. We have gained from him an insight into a program of development that has had as its main problem the application of nitric acid as an oxygen carrier. We have now heard two papers dealing with particular oxygen carriers, those of Mr. Walter and Mr. Zborowski. I wish now to invite discussion of these two papers both of which include practical application in their scope. Does anyone wish to ask a question or take the floor?

Hoffmann: Mr. Zborowski mentioned at the end of his paper the intermittent rocket unit. In recent years, I have carried out experiments on intermittent rocket and R-L units. [NACA comment: R-L designates a power plant combining the use of rocket (oxygen-carrying) propellants with the intermittent combustion and tidal air induction principles of the intermittent ram jet.] I believe it would be useful to outline briefly the important features of this field of work:

The unit, for example a tube, is charged either axially or from the side with propellant (that is, oxygen carrier plus fuel) for a certain length L_Z (combustion-chamber length). After ignition, which may occur at any point, the combustion and the expulsion of the high-pressure gases occur. The approximate course of pressure variation at the thrust plate, shown in figure D-1, may be derived from the quartz-crystal pressure-recorder charts, the evaluation of which is difficult because of the low natural frequencies of the pickup units.

After the steep rise of pressure that is characteristic of combustion at constant volume with an oxygen mixture, an expansion of the gases begins that as the result of inertia is continued to a pressure p_u, which in the test-stand experiment is lower than the outside atmospheric pressure p_a. The mean reaction pressure exerted on the unit is in accord with the equation:

$$R = P_m F = \frac{F}{T} \int_0^T (p_i - p_a)\, dt$$

Because the potential energy made available in the combustion chamber is transformed into kinetic energy of the outflowing jet, the distribution of pressure along the length of the tube is nonuniform. At the outflow end a pressure diagram, which resembles the variation of the sound amplitudes to which detonation processes give rise, is obtained. A very steep pressure increase and decrease is followed by the rather flat curve of the pressure of the outflowing gases.

Because of the pressure difference $p_a - p_u$, air flows in at the open end of the tube. The gas remaining in the tube is driven toward the thrust plate and compressed to the pressure p_a or even to the pressure p_s. The temperature of the gas lies above the ignition temperature of the propellant mixture, therefore when the period is of short duration the next working cycle is initiated without ignition by external means if, as in the Diesel engine, propellant is sprayed into these hot gases. If, however, the propellant supply is continuous, an automatically intermittent operation will occur if the pressure wave provides a plane of division between the fresh mixture and the outflowing gases and if autoignition is avoided by a drop in the temperature of the gas behind the pressure wave. In this case, an operating frequency establishes itself that is practically inversely proportional to the length L_Z of the combustion chamber and is independent of the length L of the tube.

For the attainment of optimum thrust, figure D-2 indicates that a tuning of the operating frequency to accord with the tube length is necessary. The device is operating in resonance if the pressure rise due to the succeeding combustion occurs at t_2 or t_3, as may be appropriate. In the case of a 324-millimeter tube operated with controlled intermittent propellant supply (gasoline-O_2 mixture) a curve of mean thrust force as a function of the tube length (fig. D-4) was obtained for operation at partial load.

The tidal air induction can be fully effective only with the optimum tube length because if $L \gtreqless L_{opt}$ then in accordance with figure D-2 the pressure p_a or p_s will not be built up in the tube because of the oscillating mass of gas.

I investigated the question as to what length of combustion chamber or as to what amount of propellant charge a proportional increase of thrust is obtained; this investigation covered tubes of various diameters. (See fig. D-5.)

In addition to the optimum tube length, there is an optimum combustion-chamber length or propellant charge. Up to $L_{Z,opt}$, the reactive force increases nearly proportionally. A further increase is possible only at the cost of greater specific consumption. These relations influence flight in tubes with blocked inlets because at a certain ram velocity the combustion-chamber length begins to exceed the optimum value and therefore a decrease in the effective thrust appears.

Increasing the tube cross section shows that with the optimum combustion-chamber length remaining practically constant and with equal specific consumption an increase of thrust approximately proportional to the tube cross section occurs.

The temperature-rise efficiency increases sharply until the point of optimum propellant charge is reached. The tidal air induction ratio of indrawn air to propellant supplied shows the opposite tendency and therefore in the region of optimum propellant charge the product of the mass of the exhaust multiplied by the mean exhaust velocity remains practically constant.

The intermittent rocket unit, in which the tidal air induction effect is secured by the sucking in of the masses of air through the open end of the unit is capable, in the test rig and with proper control of the propellant quantities, of obtaining a specific consumption lower than that of current continuous-combustion operation.

Only when intermittent rockets are combined with Paul Schmidt's jet tube is a propulsive system obtained that promises to bridge the gap between the R and the L units. The limits of the utilization of the combination, as well as its operating behavior, are mainly determined by the magnitude of the specific consumption (g/kg sec), by the weight, and by the spatial dimensions (aerodynamic resistance). The specific consumption of the combination in the test stand and in a certain speed and altitude range lies between that of the R and the L units.

Systematically conducted tests have shown that the introduction of additional air through the closed end of the tube leads to a substantial decrease in the specific consumption. The closure problem, which offered a great deal of trouble with the Schmidt jet tube, becomes a difficult problem in the case of the R-L unit because of the greater mean thrust density (kg/cm^2) and the higher pressure peaks.

I have tested both automatic and mechanically actuated closure arrangements. The mechanically actuated arrangements probably have a longer life but they involve complexity and increased weight of the propulsive system. These arrangements require a uniform behavior of the process in every cycle because otherwise the possibility of incomplete closure arises. Furthermore, the attainment of the optimum thrust shown in figure D-4 requires the tuning of the imposed frequency to the given tube length during flight in case of alteration of the external pressure. In the Paul Schmidt and Argus tubes, when the external pressure changes the corresponding operating frequency automatically establishes itself.

It therefore seems to be appropriate to strive for a simple, if possible, entirely automatic system of operation for the R-L unit also. Efforts in this direction have already been made. I should like to enumerate briefly the foremost problems yet to be solved:

1. Front-end closure arrangements

2. Selection of suitable propellant combinations

3. Arrangements for conveying and introducing the propellant

4. Cooling

5. Choice of internal and external shape of the unit to secure good thermal efficiency and low aerodynamic resistance

For the production of an R-L unit suitable for practical use, the development of which I endeavored to indicate in my research report of July 5, 1943, the close cooperation of all research and development authorities that has been Mr. Schelp's goal is absolutely necessary. I should like to call particular attention to the effort at this point.

Schelp: We early considered whether the development of intermittent rocket units should have been started long before this. The task was assigned to a certain firm. However, the effort failed at that time because the necessary basis on which to drive such a device was lacking. At that time, there would have been no point in pouring large sums into such a development as the existing basis of even theoretical knowledge of nonuniform gas dynamics was too small. The problems are very difficult and cannot be set forth as simply as would at first appear for we must not overlook the fact that these first results were secured in the test rig and will presumably be decisively altered in flying operation. In surveying the entire power-plant field, without doubt the bridge between the L unit and the R unit will be found in the so-called R-L power plants that gradually will be developed. A more exact demarcation of the scope of application of these power plants must wait upon time because precisely the results in the adjoining fields, presumably with respect to attainable output, may yet surprise us.

Zborowski: I should like to underscore Mr. Schelp's opening words because on the basis of weight economy use of gaseous propellants in power plants operated with rocket propellants seems unsuitable and therefore to this very moment it has not been possible to envision seriously the undertaking of this development.

Beyond that, in these jet tubes in particular a very critical expenditure of weight and mechanical complication may in certain cases result from the choice of the method of forced supply. If, however, as a method of forced supply for the tube we utilize directly or indirectly the gas pressure itself — and this is only possible because we have had available technical propellants with short ignition times — a unit of little mechanical complexity may then be designed. Such a unit could be operated at high frequency and in its combustion, but not in its consumption, would be like an orthodox rocket power plant independent of the density of the surrounding medium and of the velocity of its forward motion.

Schelp: It is only necessary to mention at this point that still another problem is determinative in this development. In most cases these power plants are used for the propulsion of aircraft that are manned. The most perfect power plant is of no use if its operation has effects upon the pilot that are injurious to health. The first signs of injury are becoming apparent in the pulse jet tubes and must be very earnestly studied.

Busemann: To return to the reports of Zborowski and Walter, the reports were a source of particular satisfaction in that they presented completed practical units; yet the discussion has dealt not at all with those units but has instead taken the units for granted as accomplished facts. The circumstance that a more lively discussion of these units did not arise should therefore in no way be interpreted as caused by lack of interest; on the contrary, we are very grateful for their reports on the present status of development.

Translation by Edward S. Shafer,
National Advisory Committee
for Aeronautics.

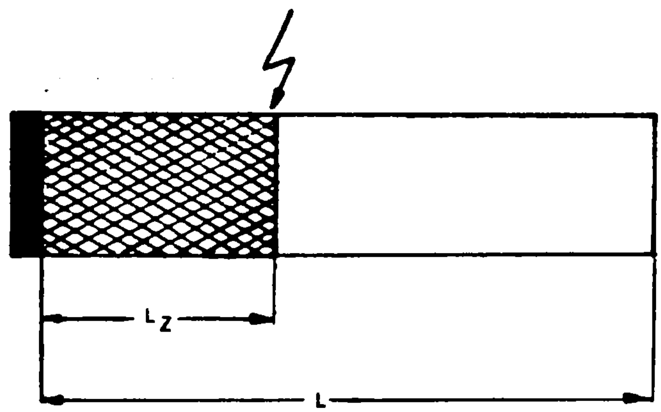


Figure D-1. - Diagram of intermittent rocket.

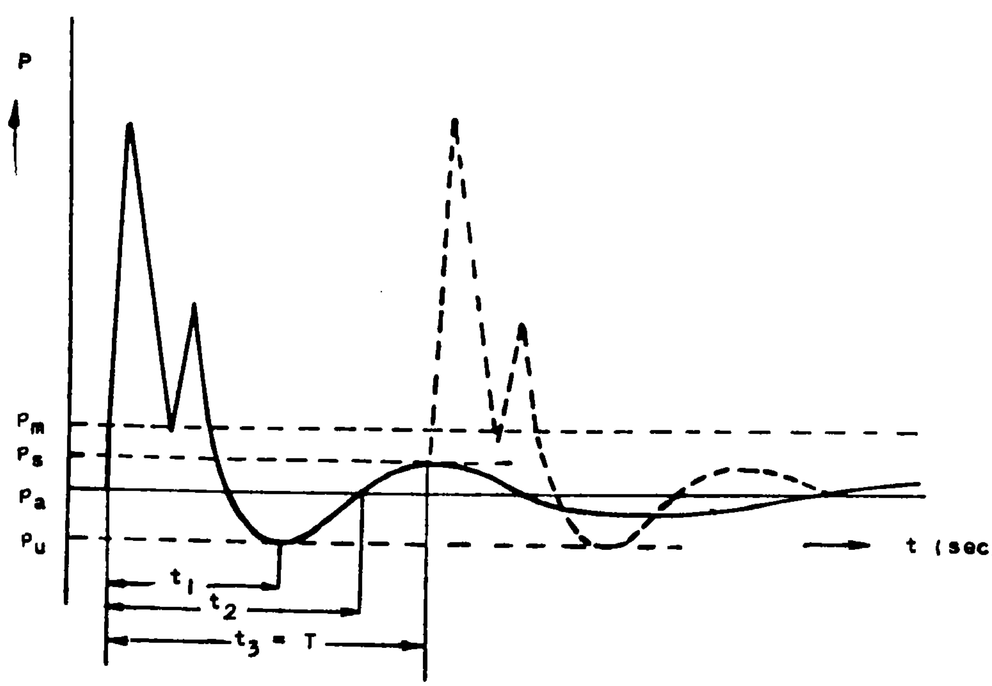


Figure D-2. - Variation of gas pressure at thrust plate.

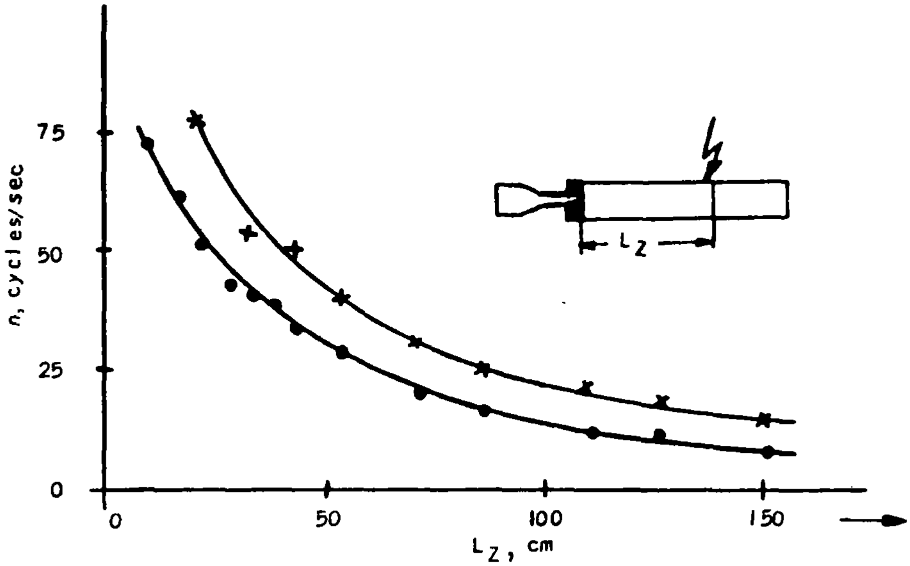


Figure D-3. - For automatic tubes with continuous feed of propellant and water plotted for two different ram velocities $n = f(L_Z)$.

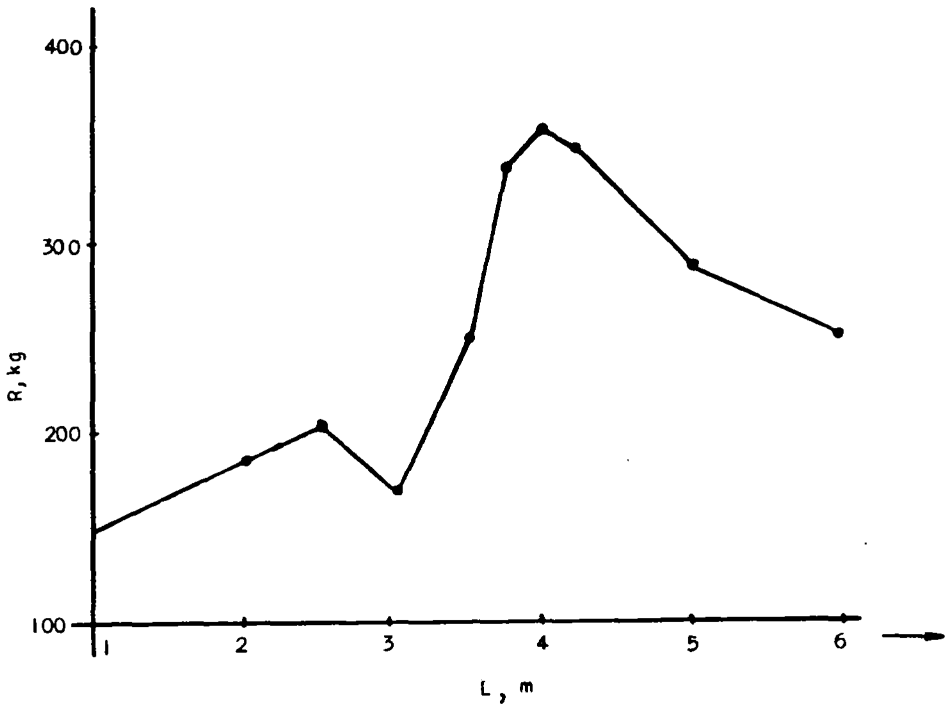


Figure D-4. - $R = f(L)$.
n = 32 cycles/sec = constant
L_Z = 64 cm = constant

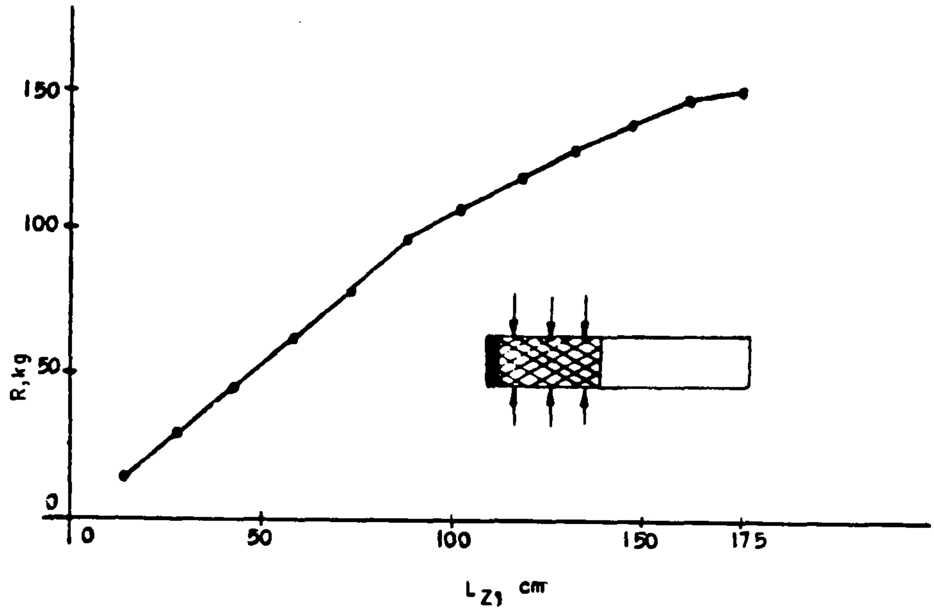


Figure D-5. - $R = f(L_Z)$
n = 32 cycles/sec = constant
L = 4 m = constant
Tube diameter, 136 mm

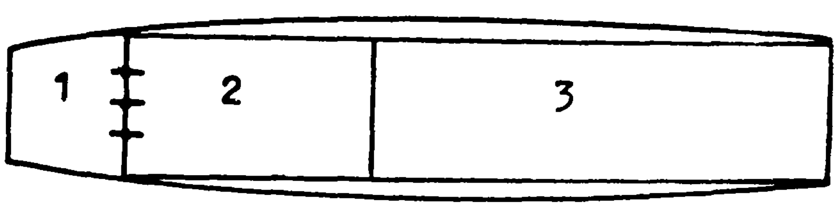


Figure D-6. - Diagram of intermittent R-L unit using air-oxygen mixture.

1 Ram-pressure chamber

2 Combustion chamber

3 Tidal air induction chamber